



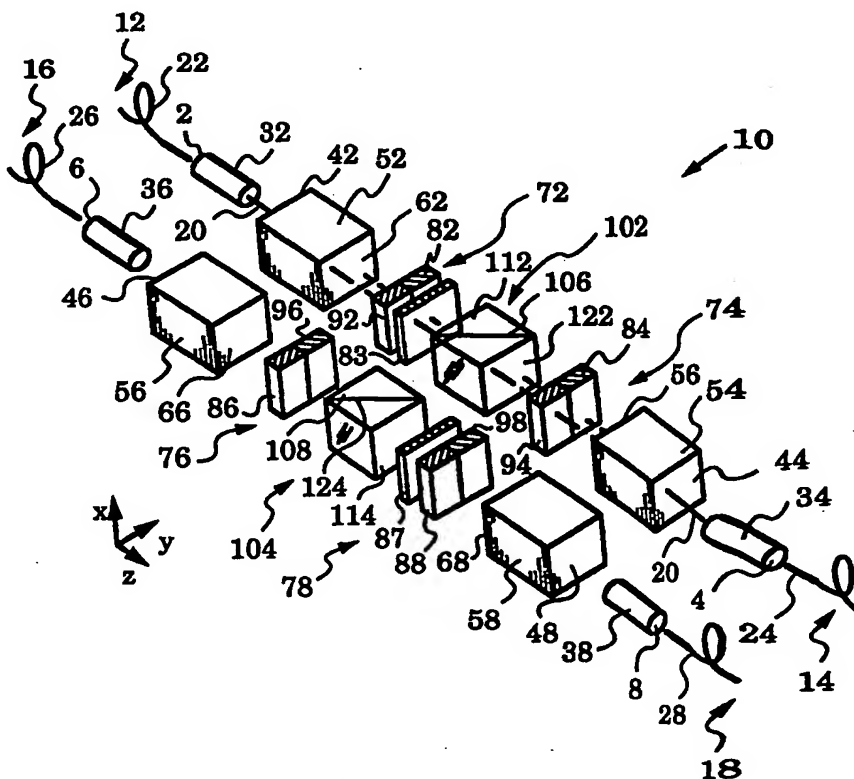
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(54) Title: MULTIPORT NON-RECIPROCAL OPTICAL DEVICE

(57) Abstract

A multi-port non-reciprocal optical device with ports (12, 14, 16, 18) for receiving and emitting a light beam consisting of a first polarization and of a second polarization orthogonal to the first polarization. The device uses birefringent walk-off elements (52, 54, 56, 58), preferably birefringent crystals with optical axes oriented at 45 degrees to the axes defining the input facets of the birefringent crystal. The crystals are positioned between the ports to split the advancing light beam along a first diagonal into an ordinary beam of the first polarization and an extraordinary beam of the second polarization. Conversely, the walk-off elements combine the ordinary beam and the extraordinary beam on the reverse or return path along the diagonal to reconstruct the light beam. Pairs of non-reciprocal rotation elements (72, 74, 76, 78) are placed in the paths of the ordinary and extraordinary beams to rotate the polarizations by 45 degrees and render them parallel or orthogonal, such that a polarization dependent deflecting element, e.g., a polarizing beam splitter/combiner (PSC) (102, 104) transmits or reflects both beams. The device can function as an optical circulator, isolator, attenuator or switch. Polarizers and/or free space isolators can be added to the device to increase isolation efficiency.



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Multiport Non-Reciprocal Optical Device

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FIELD OF THE INVENTION

This invention relates generally to non-reciprocal optical devices, and in particular to optical circulators, isolators
10 and other optical devices using birefringent walk-off elements as polarization splitters and combiners (PSCs).

BACKGROUND OF THE INVENTION

15 Single mode optical fiber has gained rapid acceptance in a variety of actual and proposed optical communications systems (e.g., CATV, fiber to the home (FTTH), wavelength division multiplexed (WDM) transmission systems, and coherent
20 communications). These technologies require versatile optical devices to perform functions such as isolating and routing of light beams.

Currently known optical isolators and circulators are only partially successful in satisfying the above requirements. To
25 be practical these components must not only be easy and inexpensive to manufacture. In addition, they have to exhibit low insertion loss at the transmission wavelengths and high isolation of unwanted signals (e.g., reflection). Isolation is particularly critical in many systems sensitive to spurious
30 reflection. For example, distributed feedback (DFB) lasers tend to be unstable when their output couples back into the lasing cavity. While expense is important in nearly all applications, it is particularly critical in high volume, low-cost projects such as FTTH. Isolation and expense are also
35 common issues in systems using optical amplifiers. That is because reflections can induce an amplifier to oscillate.

The disadvantage of primary non-reciprocal function devices is that their characteristics depend on the polarization of the input light. To solve this problem and render the devices insensitive to different polarization states, PSCs were incorporated into primary non-reciprocal devices. In the resulting polarization independent units an input PSC divides the input light beam into two light beams of linear and mutually orthogonal polarizations. These two beams pass through a reciprocal rotator and a non-reciprocal rotator, and are then combined by an output PSC.

Several polarization independent optical circulators utilizing that technique are reported. Unfortunately, their isolation levels, which were about 25 dB for a single stage circulator, remain too low for practical use. This low figure is due to rather low extinction ratios of PSCs. Recently, attempts have been made at diminishing the degrading effects on isolation deriving from imperfect polarization separation of conventional PSCs.

Thus, Yohji Fujii reports in *High Isolation Polarization Independent Optical Circulator Coupled with Single-Mode Fibers* (Journal of Lightwave Technology, Vol. 9, No. 4, April 1991) how adding birefringent plates to a conventional optical circulator obtains higher isolation. The measured isolation ranged from 29.9 to 36.79 dB. Although this approach does yield a high degree of isolation, it also creates problems. The circulator structure is intricate and the fabrication of the cross-stack polarization beam splitters is very difficult.

In *Polarization Independent Optical Circulator having High Isolation over a Wide Wavelength Range* (IEEE Photonics Technology Letters, Vol. 4, No. 2, February 1992) Yohji discloses a circulator exhibiting the same desirable isolation characteristics. This circulator is made by replacing the cross-stack polarization beam splitter with a conventional PSC containing birefringent crystal blocks. Insertion loss and

isolation of a four-port circulator made in this manner were measured at ≤ 1.9 dB and ≥ 42.3 dB, respectively. Unfortunately, four non-reciprocal rotators, eight reciprocal rotators, four birefringent crystal blocks and one common PSC are required to assemble such a circulator. This increases insertion loss, complexity and cost. Moreover, the use of many components with different thermal expansion coefficients results in poor mechanical and temperature stability in environments where wide temperature variations are experienced (e.g., FTTH).

In U.S. Patent 5,471,340 Yihao Cheng and Gary S. Duck disclose a circulator consisting of polarization dependent displacement elements, Faraday rotators, half-wave plates and a mirror which reflects the light to the next port. One advantage of this system is that the same optical element is used to separate and combine the light beams. Thus, the problems associated with tight tolerances imposed on systems with numerous components are avoided. Unfortunately, this also means that large size birefringent materials are needed to achieve sufficient separation between two differently polarized beams for collimator alignments. Consequently, the size and cost of the device increase. Furthermore, the use of half-wave plates not only decreases the extinction ratio of polarization rotation, which again reduces the isolation of the circulator, but also increases manufacturing complexity because of the necessity for optical axis alignment.

U.S. Patent 5,319,483 to Krasinski et al. addresses a polarization independent low cross-talk optical circulator. This device uses reciprocal Faraday rotation elements for controlling the polarization of the light beams. The extinction rate for this circulator is fairly low. Furthermore, the overall structure of the device is complex and its many parts necessitate exact alignment procedures. As a result, the manufacture of this device is costly and difficult.

Similarly, U.S. Patents 5,212,586 to Van Delden and 4,464,022 to Emkey describe circulators which use reciprocal Faraday rotators and require many parts. Emkey attempts to solve the separation problem by suitably shaping (slotting) the components. Van Delden solution requires very precise alignment of output ports. In both instances the manufacture is complicated. Also, the isolation is not sufficient for practical applications in new technologies (e.g., FTTH or WDM communications).

Finally, in U.S. Patent 5,204,771, Koga discloses an optical circulator which takes advantage of a pair of Faraday rotators with opposite directions of rotation. Although this device has fewer elements, its construction still requires precise alignment of the optical axis for the rotation elements. The walk-off or beam separation technique used by Koga relies on large birefringent crystals. This results in the whole device being unnecessarily sizable. Furthermore, its isolation is also rather low.

Thus, there remains a need for a single mode optical circulator, or non-reciprocal device, which has a low insertion loss and high isolation, yet can be easily manufactured and exhibits good mechanical and thermal stability. To ensure simple and low-cost manufacture, such device should not rely exclusively on half-wave plates or other rotators which require precise alignment of the optical axis.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a multi-port non-reciprocal optical device, such as an optical circulator, an optical switch or an optical attenuator with low insertion loss and a high extinction ratio

in polarization separation. In particular, the invention aims at achieving a high extinction ratio in the PSC.

5 Another object of the invention is to reduce the size of the device by optimizing the polarization separation performance of the birefringent walk-off elements.

10 It is also an object of the invention to employ non-reciprocal Faraday rotators in the device whenever possible and thereby reduce the optical axis alignment requirements imposed by reciprocal rotators. This will provide for simpler design and decrease the high rotation extinction ratio associated with reciprocal rotators.

15 Still another object of the invention is to ensure that the device makes use of the fewest parts possible and is easy to fabricate.

20 These and other objects and advantages will become more apparent after consideration of the ensuing description and the accompanying drawings.

SUMMARY OF THE INVENTION

5 These objects and advantages are attained by a multi-port non-reciprocal optical device with at least two ports for receiving and emitting a light beam. The light beam consists of radiation of a first polarization and of a second polarization orthogonal to the first polarization. A first birefringent walk-off element, preferably a birefringent
10 crystal made of a material selected from among rutile, calcite and Yttrium Orthovanadate, is positioned between the ports. The walk-off element splits the advancing light beam along a first diagonal into an ordinary beam of the first polarization and an extraordinary beam of the second polarization.
15 Conversely, the walk-off element combines the ordinary beam and the extraordinary beam on the reverse or return path along the diagonal to reconstruct the light beam.

20 A pair of reciprocal rotation elements, such as half-wave plates are placed in the paths of the ordinary and extraordinary beams to render the first and second polarizations parallel. This is done, for example, by rotating the first polarization by 45° and the second polarization by 45° as well, such that both polarizations are
25 oriented in a common polarization direction. When necessary, a polarizer having its polarization axis parallel to the common polarization direction can be used at any stage in the device of the invention to ensure that only the correct polarization passes through. Any type of polarizing element
30 can be employed for this purpose.

A polarization dependent deflecting element, e.g., a polarizing splitter combiner (PSC), receives the ordinary beam and the extraordinary beam. The deflecting element is
35 characterized by a reflecting polarization and a transmitting polarization which is orthogonal to the reflecting polarization. The deflecting element can be a polarizing beam

splitter. Preferably, the beam splitter is made of a pair of right angle prisms cemented hypotenuse-face to hypotenuse-face. Furthermore, a multilayer dielectric film is preferably placed between the pair of prisms. Thus, when the polarization of the ordinary and extraordinary beams correspond to the transmitting polarization the beam splitter passes them. In the other case, when the polarizations of these beams are parallel to the reflecting polarization, the beam splitter reflects both.

A pair of reciprocal rotation elements such as half-wave plates or non-reciprocal rotation elements, preferably non-reciprocal Faraday rotators such as latching Faraday rotators or ordinary Faraday rotators, is placed in the paths of the ordinary and extraordinary beams for rendering the first and second polarizations orthogonal. This is best accomplished by rotating the first polarization by 45° and also rotating the second polarization by 45° . If half-wave plates are used, a polarizer can be placed between the beam splitter and the half-wave plates to ensure that the polarizations of the two beams are parallel and that only the correct polarization passes through.

A second birefringent walk-off element is positioned between the ports for splitting the light beam or combining the ordinary and extraordinary beams. This element is analogous to the first one. Preferably, both walk-off elements have their optical axes oriented at 45° to the axes (x and y) defining input facets of the birefringent crystal.

The input ports are GRIN lenses. These are well-suited for receiving and emitting the light beam. Further, the light beam can be received and emitted by single mode or multi-mode optical fibers. The number of ports may vary.

The use of reciprocal rotators such as half-wave plates after the first walk-off element and before the last is desirable

since non-reciprocal rotation elements such as Faraday rotators introduce optical path aberrations up to 1° due to tolerances in manufacturing. The aberration must be checked for each Faraday rotator. Half-wave plates are uniform, inexpensive and reliable. Circulators using half-wave plates have lower insertion losses, lower polarization dependent losses and higher overall efficiency.

A detailed description of the method is set forth below in reference to the drawing figures.

DESCRIPTION OF THE FIGURES

- Fig. 1 is an isometric view of a multi-port non-reciprocal optical device according to the invention.
- Fig. 2 is an isometric view of a walk-off element from the device of Fig. 1.
- Fig. 3 is an isometric view of a pair of half-wave plates and a polarizer from the device of Fig. 1.
- Fig. 4A-C are diagrammatic views illustrating the polarization rotations in the device of Fig. 1.
- Fig. 5 is an isometric view of a pair of Faraday rotators from the device of Fig. 1.
- Fig. 6 is a plan top view of a different non-reciprocal optical device according to the invention.
- Fig. 7A-C are diagrammatic views illustrating the polarization rotations in the device of Fig. 6.
- Fig. 8 is a plan top view of yet another non-reciprocal optical device according to the invention.
- Fig. 9A-C are diagrammatic views illustrating the polarization rotations in the device of Fig. 8.
- Fig. 10 is a plan top view of a three-port circulator according to the invention.

DETAILED DESCRIPTION

An embodiment of a four port non-reciprocal optical device 10 according to the invention is shown in Fig. 1. For clarity device 10 is depicted in an exploded but aligned state. A Cartesian coordinate system is used to clearly identify the various directions and orientations. Device 10 has four ports 12, 14, 16 and 18 fed by corresponding optical fibers 22, 24, 26 and 28. All ports 12, 14, 16 and 18 are designed for receiving and emitting light. Fibers 22, 24, 26 and 28 are multi-mode or single mode fibers. Lenses 32, 34, 36 and 38 assigned to corresponding ports 12, 14, 16 and 18 serve to couple light into and out of device 10. It is preferable that faces 2, 4, 6, 8 of lenses 32, 34, 36, 38 be slanted and coated. The slant acts to limit unwanted back reflection while the coating improves the in-coupling efficiency. Techniques to achieve this result are well-known in the art. In the present embodiment lenses 32, 34, 36, 38 are of the GRIN-type and their faces 2, 4, 6, 8 are slightly inclined.

A light beam 20 enters device 10 through port 12. Once admitted it is incident on an input facet 42 of a birefringent walk-off element 52. In fact, element 52 is one of four analogous walk-off elements 52, 54, 56 and 58 having corresponding input facets 42, 44, 46 and 48. Suitable materials for elements 52, 54, 56 58 include rutile, calcite, Yttrium Orthovanadate and the like. In other words, walk-off elements 52, 54, 56, 58 are birefringent crystals.

The optical axes 90 of all elements 52, 54, 56, 58 are in the plane oriented at 45° to the axes defining input facets 42, 44, 46 and 48. This is shown in detail by Fig. 2 using element 52 as an example. A vector 91 defines the 45° angle to the sides of facet 42. Optical axis 90 is oriented an an angle θ to vector 91. In fact, vector 91 and optical axis 90 define the above-mentioned plane which is inclined at 45° to the x-z plane. The magnitude of angle α is obtained from the well-known relation:

$$\tan(\alpha) = \left(\frac{n_o^2}{n_e^2} - 1 \right) \frac{\cot(\theta)}{1 + \frac{n_o^2}{n_e^2} \cot^2(\theta)}$$

In the present case θ is the angle described by vector 91 and is thus equal to 45° ($\theta = 45^\circ$). When light beam 20 is split into an ordinary beam 130 and an extraordinary beam 132 the two experience difference refractive indices inside crystal 52. In particular ordinary beam 130 sees the refractive index n_o and extraordinary beam 132 experiences the refractive index n_e .

A walk-off distance D_{wo} in element 52 is defined as follows:

$$D_{wo} = a \tan(\alpha)$$

where a is the length of element 52 traversed by beams 130 and 132 as indicated. The reason for the separation of the two beams is due to the difference in the refractive indices. As a result, extraordinary beam 132 will travel forward or advance along a short diagonal 134 diverging quickly from the straight path taken by ordinary beam 130. Of course, when ordinary beam 130 and extraordinary beam 132 are on their return path, they will be efficiently combined along diagonal 134. This issue is important to the invention since it allows to minimize the size of birefringent crystals 52 through 58.

During the walk-off, ordinary beam 130 will retain a first polarization 140 and extraordinary beam 132 will have a second polarization 142. Polarizations 140 and 142 are orthogonal to each other.

Referring again to Fig. 1, output facets 62, 64, 66 and 68 face corresponding pairs of non-reciprocal rotation elements 72, 74, 76, 78 each consisting of two individual rotators 82;92, 84;94, 86;96 and 88;98. The rotation sense of each rotator 82;92, 84;94, 86;96 and 88;98 is discussed below.

Preferably, rotators 72 and 78 comprise half-wave plates 82;92, 88;98 and polarizers 83 and 87. The latter are used in the preferred embodiment to increase isolation, i.e., reduce light transmission from port 14 to port 12. Of course, device 10 will also operate without polarizers 83 and 87. Rotators 84;94, and 86;96 are either regular Faraday rotators or latching Faraday rotators. The latter operate without a bias magnet and are consequently preferred. A person skilled in the art will know how to adapt either of these components to device 10. It is important to note that the overall dimensions of device 10 can be minimized when using latching Faraday rotators 82;92, 84;94, 86;96 and 88;98 since the magnetic material is incorporated within such a rotator.

Fig. 3 illustrates the operation of rotation element 72 consisting of half-wave plates 82, 92 and polarizer 83. Half-wave plate 82 has a principle plane 85 oriented at an acute angle of 22.5° to first polarization 140.

The polarization direction of polarized light entering a half wave plate will make an acute angle β with a principle plane of the half-wave plate. Half-wave plates work by introducing a phase shift between the component of polarization which is parallel to the optic axis of the half-wave plate and the component which is perpendicular to the optic axis. The result of this phase shift is a rotation of the polarization of the incident light by an angle of 2β .

In the present case, half-wave plate 92 has a principle plane 95 oriented at an acute angle of 22.5° to second polarization 142. This causes second polarization 142 of extraordinary beam 132 to be rotated by 45° to the position shown. At the same time, first polarization 140 of ordinary beam 130 is also turned by 45°. The two 45° polarization rotations are opposite in sense so that polarizations 140 and 142 emerge parallel. Beams 130 and 132 pass through polarizer 83 whose transmission axis is aligned to pass the emerging first and

second polarizations 140 and 142. Polarizer 83 improves the isolation of device 10 as explained below.

Returning to Fig. 1, one notes two polarization dependent deflecting elements 102 and 104 positioned between pairs of elements 72, 74, 76, 78. In fact, elements 102 and 104 are polarizing beam splitters and combiners (PSCs). The property of splitters 102 and 104 dictates that light having a transmitting polarization will pass through splitters 102 and 104. Meanwhile, light having a reflecting polarization will be reflected. This function is ensured by reflecting films 106 and 108. The latter may be made of a multilayer dielectric films. Note that the transmission axes of polarizers 83 and 87 are aligned to ensure that only light of the correct polarization reaches birefringent walk-off elements 52 and 58, thereby eliminating light of unwanted polarization being transmitted to port 12 and port 18, and increasing isolation performance.

In general, beam splitters 102 and 104 are made of a pair of right angle prisms 112; 122 and 114; 124. Multilayer films 106 and 108 are sandwiched by prisms 112; 122 and 114; 124, which are cemented together hypotenuse-face to hypotenuse-face.

The operation of device 10 is best visualized by referring back to Fig. 1 and following the diagrams of Figs. 4A-4C. These drawings illustrate light beam 20 traveling from port 12 to port 14, from port 14 to port 16 and from port 16 to port 18. The polarization rotations are shown explicitly. After entering device 10 through port 12 in the direction indicated by arrow A, first and second polarizations 140 and 142 of beams 130 and 132 are "walked-off" in element 52 by distance D_{wo} . Then, rotators 82 and 92 rotate polarizations 140 and 142 by 45° clockwise and counter-clockwise, respectively. At this point, polarizations 140 and 142 are parallel to each

other. Of course, polarizer 83 introduces no additional polarization rotation.

In beam splitter 102 polarizations 140, 142 are aligned with the intrinsic transmitting polarization and are thus passed on to rotators 84 and 94. Inside rotators 84 and 94 polarizations 140, 142 are rotated by another 45° each and are again orthogonal to each other. Then, inside element 54, following upon the return path, ordinary and extraordinary beams 130 and 132 are combined again, as indicated by merged polarizations 140, 142, and delivered to port 14.

Clearly, device 10 is a circulator, since no light can return to original port 12 by following the path of light beam 20 from port 14 back to port 12. Instead, as show in Fig. 4B, light beam 20 passes from port 14 to port 16 along the direction indicated by arrow B. The "walk-off" between beams 130 and 132 of polarizations 140 and 142 occurs in crystal 54. Clockwise and counter-clockwise 45° rotations in rotators 84 and 94 render polarizations 140 and 142 parallel. In this state, polarizations 140 and 142 are aligned with the reflecting polarization of beam splitter 102.

Beams 130 and 132 are consequently reflected by splitter 102 or, more precisely, by film 106 along a direction perpendicular to arrow B (x-direction) and travel to splitter 104, where they are aligned with splitter's 104 reflecting polarization. Again reflected, this time along the direction of arrow B, beams 130 and 132 pass through rotators 86 and 96. These rotate polarizations 140 and 142 by 45° to render them orthogonal. Crystal 56 reunites beams 130 and 132 into light beam 20, and the latter exits device 10 through port 16.

Fig. 4C shows how light beam 20 passes from port 16 to port 18 along the direction indicated by arrow A. As before, the "walk-off" takes place in crystal 56. Rotators 86 and 96 induce 45° rotations of polarizations 140 and 142, such that

they are parallel and aligned with the transmitting direction of splitter 104. Beams 130 and 132 thus pass through splitter 104 and polarizer 87 to rotators 88 and 98 to be rotated such that their polarizations 140 and 142 are again orthogonal. Crystal 58 rejoins beams 130 and 132 into light beam 20 which then issues forth through port 18.

Fig. 5 illustrates the operation of pair of non-reciprocal rotation elements 74 consisting of rotators 84 and 94. Corresponding magnetic fields B_1 and B_2 are generated by suitable sources such as permanent magnets. In the case of latching-type rotators 84, 94 the material of rotators 84 and 94 is appropriately magnetized to set up fields B_1 and B_2 . The direction of fields B_1 and B_2 determines how the polarization of light passing through rotators 84 and 94 is altered. In this embodiment fields B_1 and B_2 are anti-aligned to produce 45° contrary polarization rotations. This causes first polarization 140 of ordinary beam 130 to rotate by 45° to the position shown. At the same time, second polarization 142 of extraordinary beam 132 is also turned by 45°. The two 45° polarization rotations are opposite in sense. As a result, first and second polarizations 140 and 142 end up being parallel.

Device 10 is a multi-port non-reciprocal optical device, in particular a circulator, with a low insertion loss and a high extinction ratio in polarization separation. This is chiefly due to the use of walk-off elements 52, 54, 56 and 58. In a three port circulator, as described below, polarization beam splitter 104 can be replaced by a highly reflective element such as a reflecting prism or a glass plate with a highly reflective coating while retaining the same advantages.

Further, the orientation of polarization axis 90 in the plane set at 45° to the sides of input facets of crystals 52, 54, 56 and 58 the polarization separation performance is optimized. The "walk-off" along diagonal 134 allows one to use non-

reciprocal rotators 84;94 and 86;96 immediately past crystals 54 and 56. This eliminates the need for precise alignment procedures (commonly required to properly orient the optical axes of half-wave plates), reduces the number of parts, and greatly simplifies the design of circulator 10 in comparison to prior art units.

Another circulator 200 according to the invention is shown exploded and in top plan view in Fig. 6. In this embodiment circulator 200 has four ports 202, 204, 206 and 208 equipped with lenses 212, 214, 216, 218 and fed by optical fibers 222, 224, 226 and 228. In this view it is apparent that the faces of lenses 212, 214, 216, 218 are inclined to improve the in-coupling efficiency of light.

Birefringent walk-off elements 232, 234, 236 and 238 are set up as in the above-discussed embodiment for separating the input light into its ordinary and extraordinary component beams (not shown). Half-wave plates 242;252 and 248;258 are set on polarization dependent deflecting elements 260 and 264. Non-reciprocal Faraday rotators 244;254 and 246;256 are set on polarization dependent deflecting element 262. Elements 260 and 264 are prisms with reflective films 266 and 268. Meanwhile, element 262 is a full beam splitter with reflecting film 280.

The operation of this embodiment is explained by the diagrams in Figs. 7A-C. For the purpose of this discussion it will be assumed that the same light beam 20 as used in the previous embodiment is introduced into port 202 along the direction indicated by arrow A. Once again, a "walk-off" by distance D_{wo} takes place in element 232 to yield ordinary and extraordinary beams 130 and 132 with orthogonal polarizations 140 and 142. Rotators 242 and 252 turn these polarizations by 45° to render them parallel and aligned with the reflecting direction of prism 260 and beam splitter 262. Consequently, beams 130 and 132 are reflected by film 266 along arrow C into

beam splitter 262. There, beams 130 and 132 are once again reflected by film 280 along arrow B to rotators 244 and 254 and subsequent element 234. Recombined light beam 20 exits circulator 200 through port 204.

5 When light beam 20 is introduced through port 204 it passes through element 234 and separates into beams 130, 132 which pass through rotators 244, 254 to splitter 262. The direction of propagation is indicated by arrow A. Both beams 130 and
10 132 have their polarizations 140 and 142 aligned with the transmitting direction of splitter 262 and thus continue on their path to rotators 246 and 256. The latter rotate polarizations 140 and 142 to render them orthogonal and pass beams 130 and 132 to element 236. Here, light beam 20 is
15 reconstructed and then emitted through port 206.

The progress of beam 20 from port 206 to port 208 along arrows B, C and A is illustrated in Fig. 7C. The steps and polarization rotations are closely related to those explained
20 in Fig. 7A.

Device 200 is an efficient, simple and low-cost circulator endowed with the aforementioned advantages. Its geometry, in particular the arrangement of ports 202, 204, 206 and 208
25 makes it suitable for many different applications.

Yet another embodiment of a device 300 according to the invention is illustrated in Fig. 8. Except for the different geometrical arrangement of ports 302, 304, 306, 308 and a
30 different set of polarization independent deflecting elements 342, 346, 350, 352 and polarization dependent deflecting elements 344 and 348 this device is similar to the previous embodiments. It has fibers 312, 314, 316, 318 coupled into device 300 through lenses 322, 324, 326, 328 leading to walk-
35 off elements 332, 334, 336 and 338. Furthermore, device 300 also has half-wave plates 362;372, 368;378, polarizers 382, 388, and non-reciprocal Faraday rotators 364;374, 366;376. As

in the previous embodiments, polarizers 382 and 388 are optional and their main function is to improve the isolation efficiency of device 300.

5 In operation device 300 proves to be an optical circulator. The diagrams of Figs. 9A-C show how light beam 20 propagates from port to port. This process is analogous to those described above. In particular, Fig. 9A shows the progress of beam 20 from port 302 to port 304 along directions indicated
10 by arrows A, B and C. Fig. 9B shows beam 20 on its path from port 304 to 306 through four deflecting elements 344, 346, 350 and 348. Finally, the passage of beam 20 from port 306 to 308 can be seen in Fig. 9C.

15 The additional advantage of circulator 300 is that all ports 302, 304, 306 and 308 are arranged on the same side. This is advantageous for applications under geometrical constraints from all but one side.

20 Fig. 10 illustrates yet another non-reciprocal optical device 400 with three ports 402, 404 and 406. Device 400 functions as a circulator and uses fibers 412, 414, 416 in conjunction with lenses 422, 424 and 426 for efficient transmission of light. It also has three walk-off elements 432, 434 and 436
25 arranged facing three sides of a beam splitter 450. The latter has half-wave plates 462;472, 464;474 and polarizers 482, 484 on the sides facing elements 432 and 436, and non-reciprocal Faraday rotators 466;476 on the side facing element 434.

30 Standard free-space isolators 492 and 494 are placed between lenses 422, 424 and walk-off elements 432 and 434 to increase isolation of port 404 to port 402, and port 406 to port 404. Isolator 492 only transmits light in the direction shown by
35 arrow B.

Device 400 operates according to the same principles-as the previous embodiments. The advantage of its design resides in the efficient use of a single beam splitter 450. Further, losses due to multiple reflections and scattering are minimized in this structure. Ports 402, 404 and 406 are far apart for easy access and connection.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. In particular, the structures discussed above can be used as optical isolators, attenuators or switches. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A multiport optical non-reciprocal device comprising:
 - a) at least two ports for receiving and emitting a light beam having a first polarization and a second polarization orthogonal to said first polarization;
 - b) a first birefringent walk-off means positioned between said at least two ports for splitting said light beam when advancing along a first diagonal into an ordinary beam of said first polarization and an extraordinary beam of said second polarization, and for combining said ordinary beam and said extraordinary beam when returning along said first diagonal into said light beam;
 - c) a first pair of non-reciprocal rotation means placed in the paths of said ordinary beam and of said extraordinary beam for rendering said first polarization and said second polarization parallel;
 - d) a polarization dependent deflecting means for receiving said ordinary beam and said extraordinary beam, said polarization dependent deflecting means having a transmitting polarization and a reflecting polarization orthogonal to said transmitting polarization;
 - e) a second pair of non-reciprocal rotation means placed in the paths of said ordinary beam and of said extraordinary beam for rendering said first polarization and said second polarization orthogonal;
 - f) a second birefringent walk-off means positioned between said at least two ports for splitting said light beam when advancing along a second diagonal into said ordinary beam of said first polarization and said extraordinary beam of said second polarization, and for combining said ordinary beam and said extraordinary beam when returning along said second diagonal into said light beam.

- 1 2. The device of claim 1, wherein said first birefringent
2 walk-off means and said second birefringent walk-off
3 means comprise birefringent crystals.
4
- 1 3. The device of claim 2, wherein each one of said
2 birefringent crystals has an optical axis in a
3 plane inclined at 45° to the axes defining input
4 facets of said birefringent crystals.
5
- 1 4. The device of claim 1, wherein said polarization
2 dependent deflecting means is at least one polarizing
3 beam splitter.
4
- 1 5. The device of claim 4, wherein said at least one
2 polarizing beam splitter comprises a pair of right
3 angle prisms cemented hypotenuse-face to
4 hypotenuse-face.
5
- 1 6. The device of claim 5, further comprising a
2 multilayer dielectric film between said pair
3 of right angle prisms.
4
- 1 7. The device of claim 1, wherein said first pair of non-
2 reciprocal rotation means render said first
3 polarization and said second polarization parallel to
4 said transmitting polarization.
5
- 1 8. The device of claim 1, wherein said first pair of non-
2 reciprocal rotation means render said first
3 polarization and said second polarization parallel to
4 said reflecting polarization.
5
- 1 9. The device of claim 1, wherein said first pair of non-
2 reciprocal rotation means comprises a first pair of
3 non-reciprocal Faraday rotators which render said
4 first polarization and said second polarization

parallel by rotating said first polarization by 45°
and by rotating said second polarization by 45°.

10. The device of claim 1, wherein said second pair of non-reciprocal rotation means comprises a second pair of non-reciprocal Faraday rotators which render said first polarization and said second polarization perpendicular by rotating said first polarization by 45° and by rotating said second polarization by 45°.

11. The device of claim 1, wherein said first pair of non-reciprocal rotation means and said second pair of non-reciprocal polarization rotation means comprise a first pair of latching Faraday rotators and a second pair of latching Faraday rotators.

12. The device of claim 1, wherein said first pair of non-reciprocal rotation means and said second pair of non-reciprocal polarization rotation means comprise a first pair of Faraday rotators and a second pair of Faraday rotators.

13. The device of claim 1, wherein said at least two ports comprise GRIN lenses for shaping said light beam for reception by said device and for shaping said light beam for emission from said device.

14. The device of claim 1, wherein first birefringent walk-off means and said second birefringent walk-off means are made of a material selected from the group consisting of rutile, calcite and Yttrium Orthovanadate.

15. The device of claim 1, further comprising optical fibers for receiving and emitting said light at said at least two ports.

1 16. The device of claim 15, wherein said optical
2 fibers are all single mode fibers.
3

1 17. The device of claim 15, wherein said optical
2 fibers are all multi-mode fibers.
3

1 18. The device of claim 1, comprising at least three ports
2 arranged to sequentially pass said light beam between
3 said four ports such that said device is a circulator.
4

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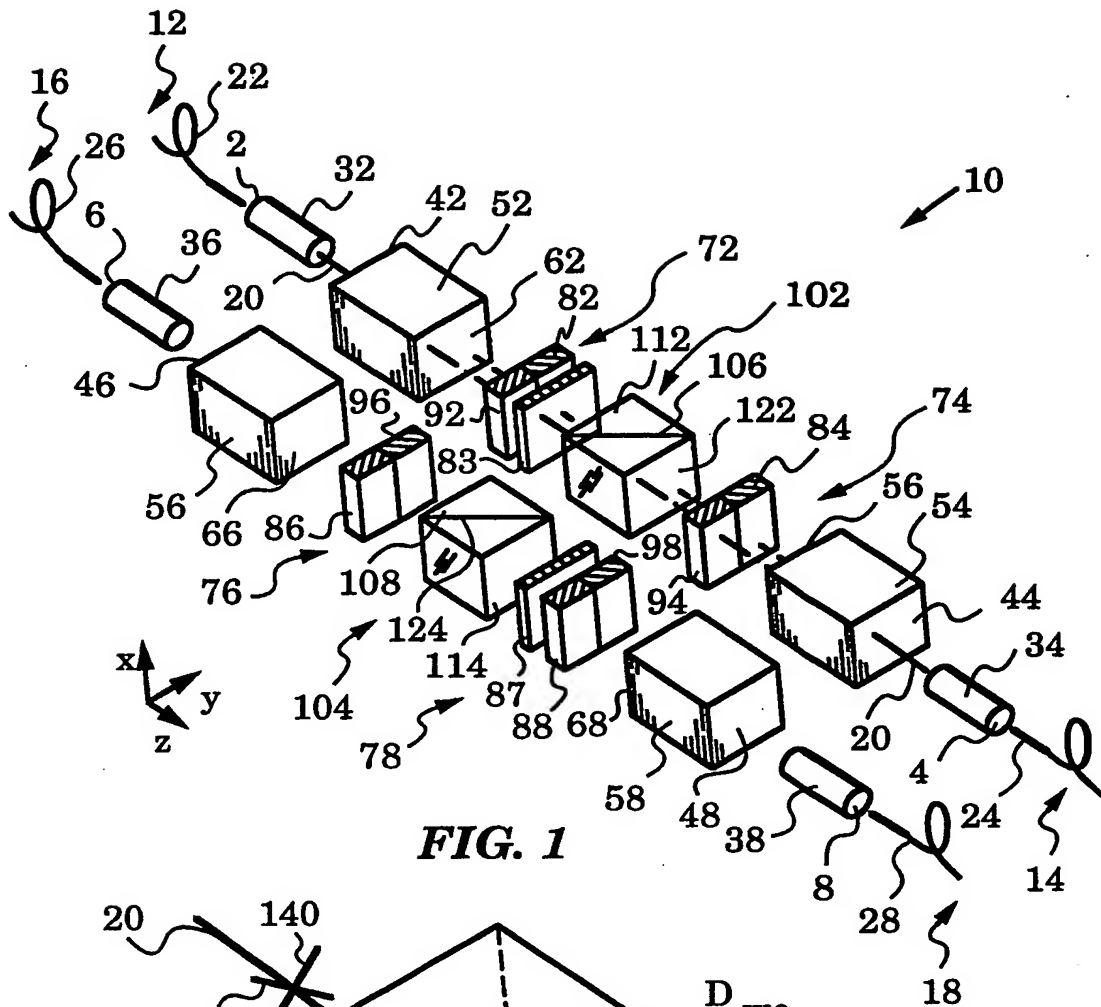


FIG. 1

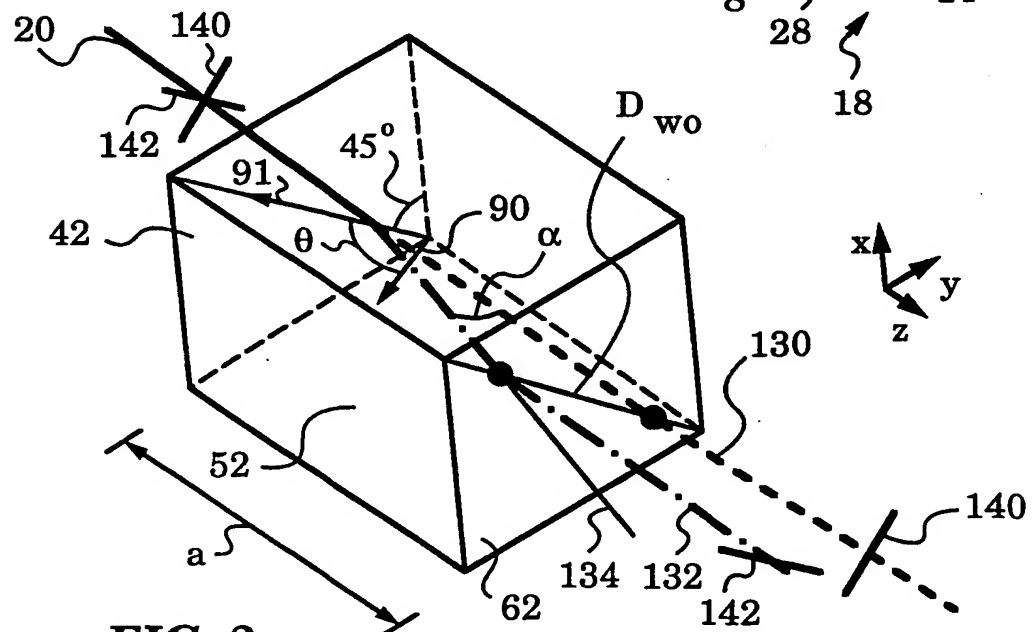


FIG. 2

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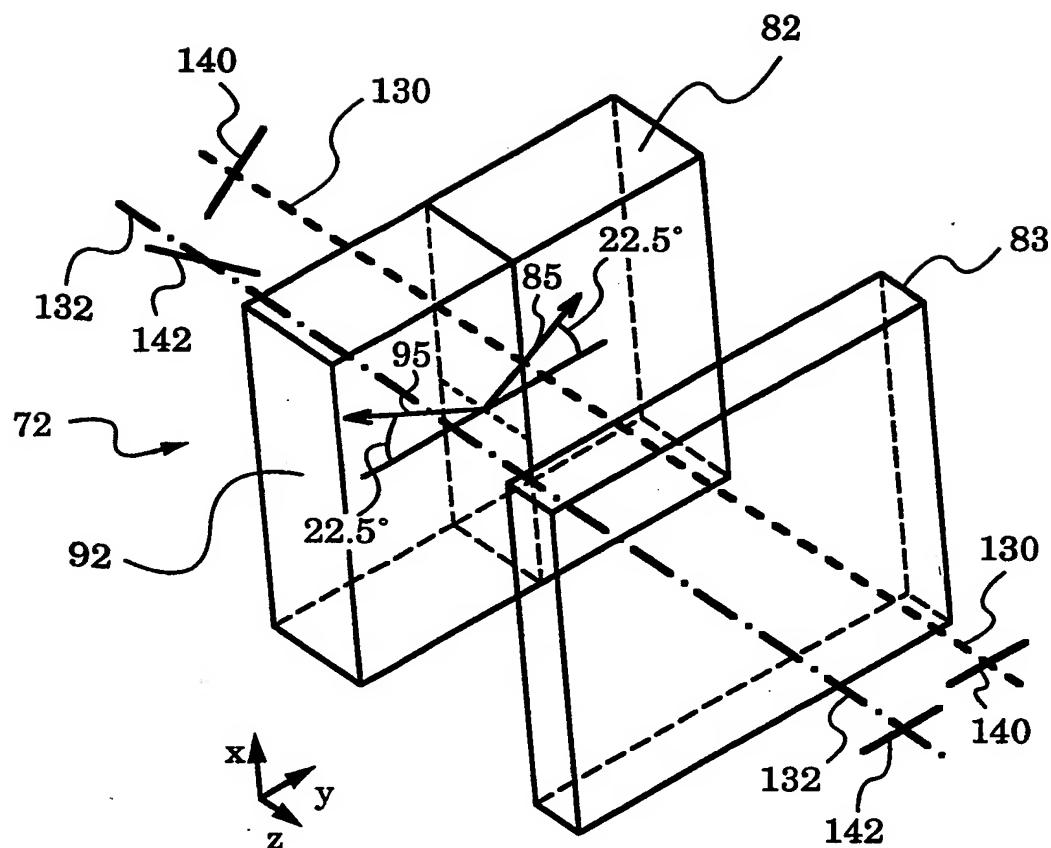


FIG. 3

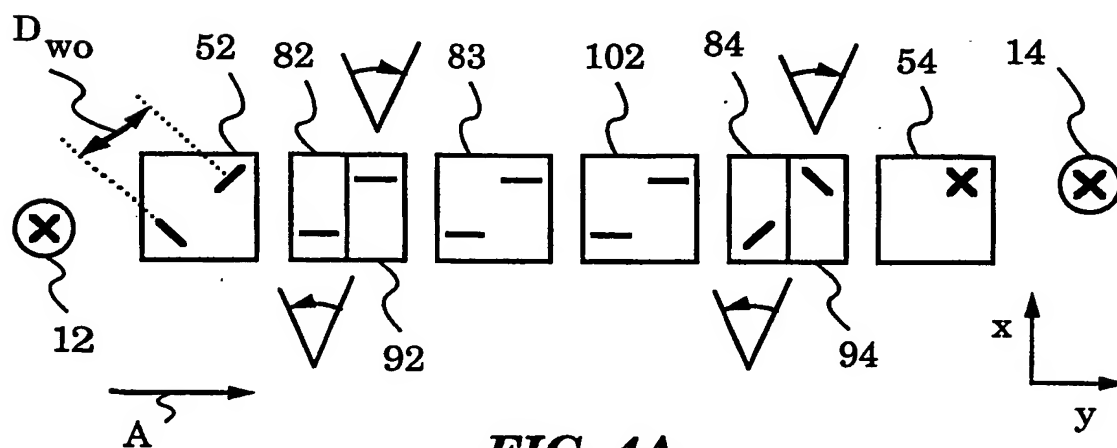
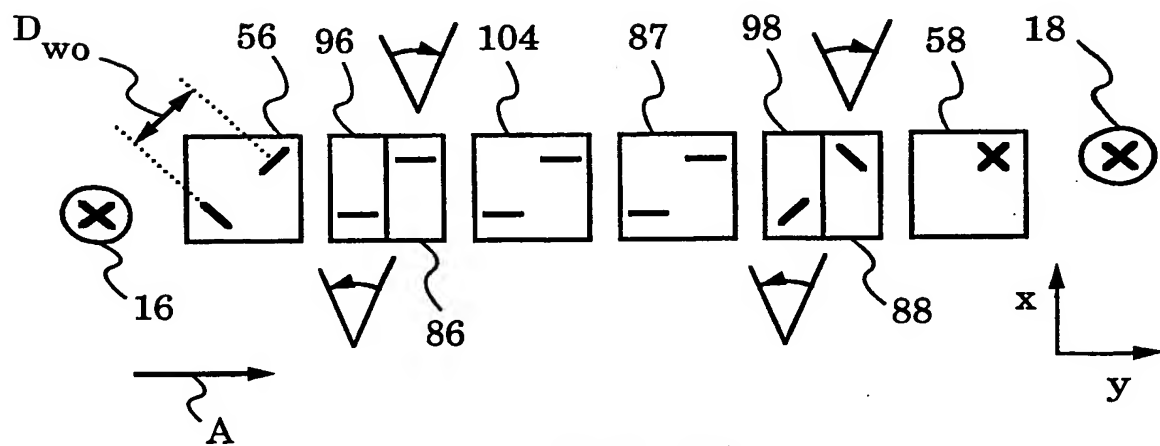
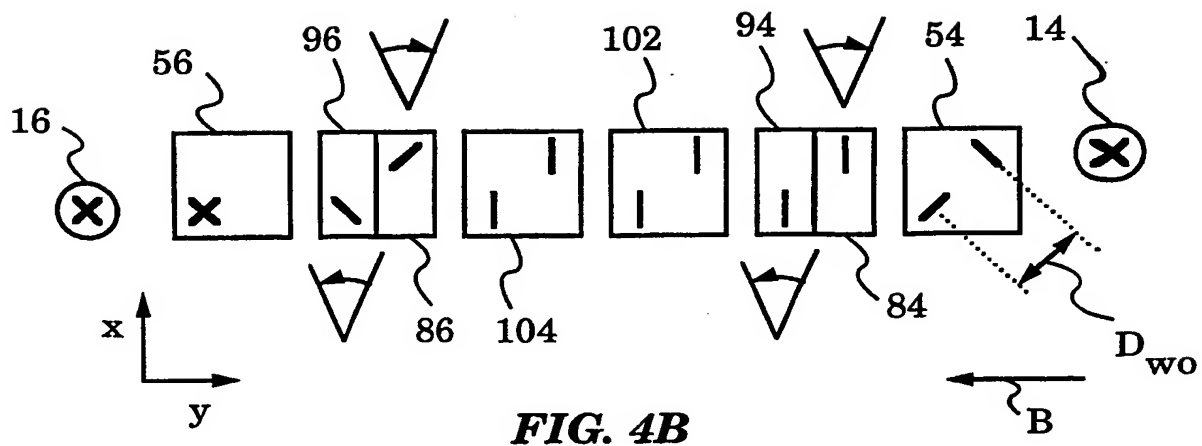


FIG. 4A

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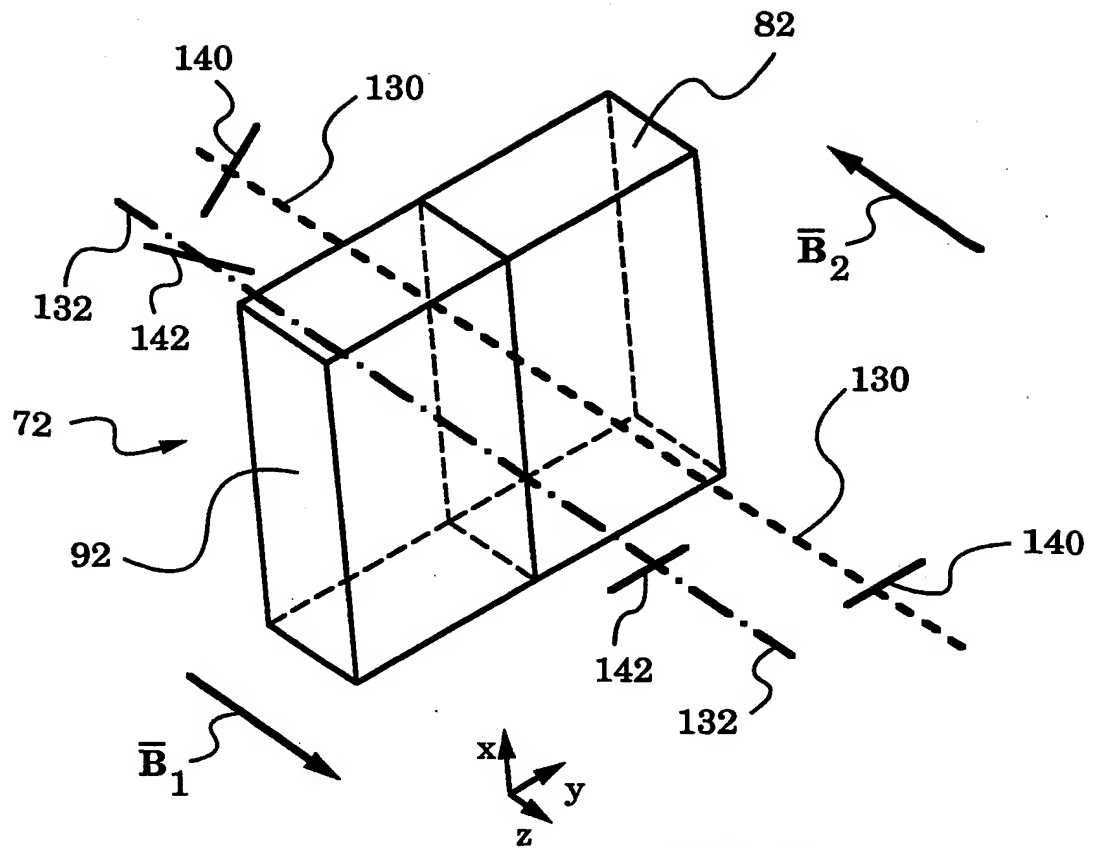


FIG. 5

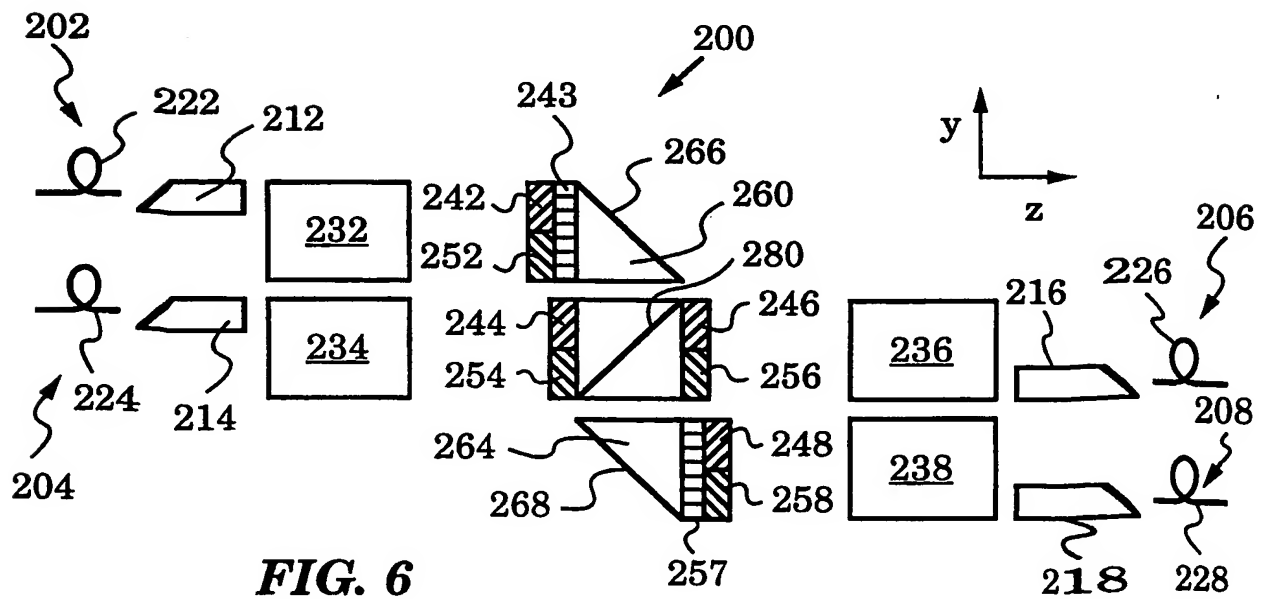


FIG. 6

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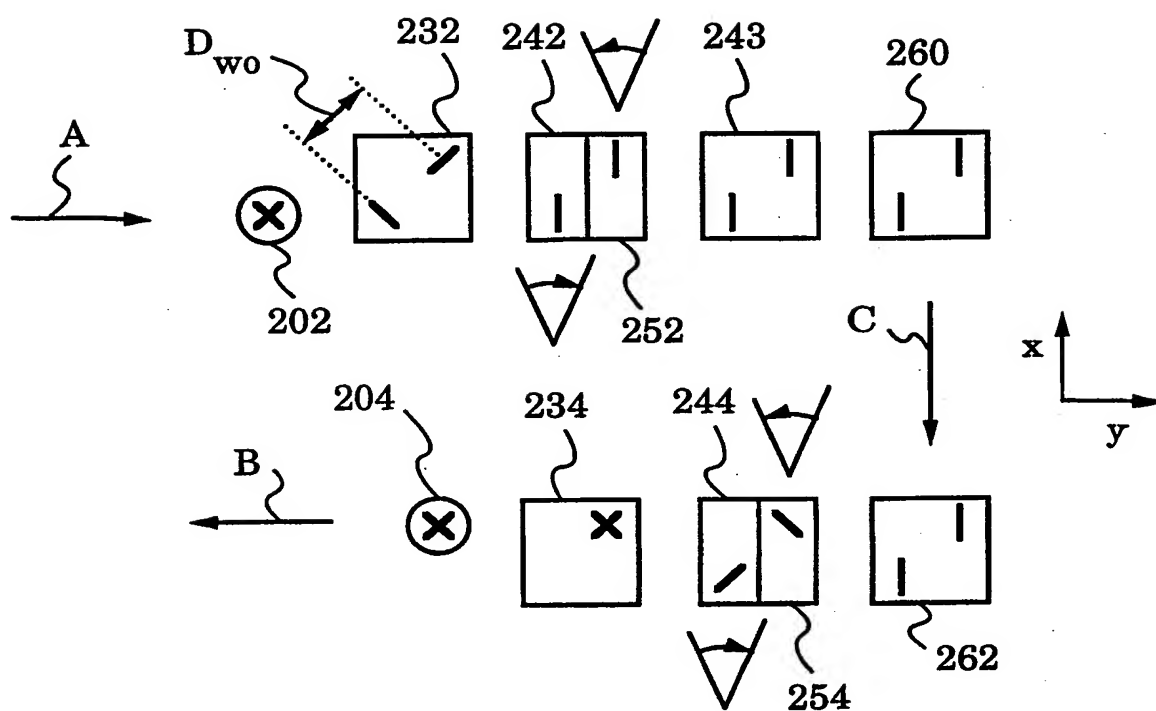


FIG. 7A

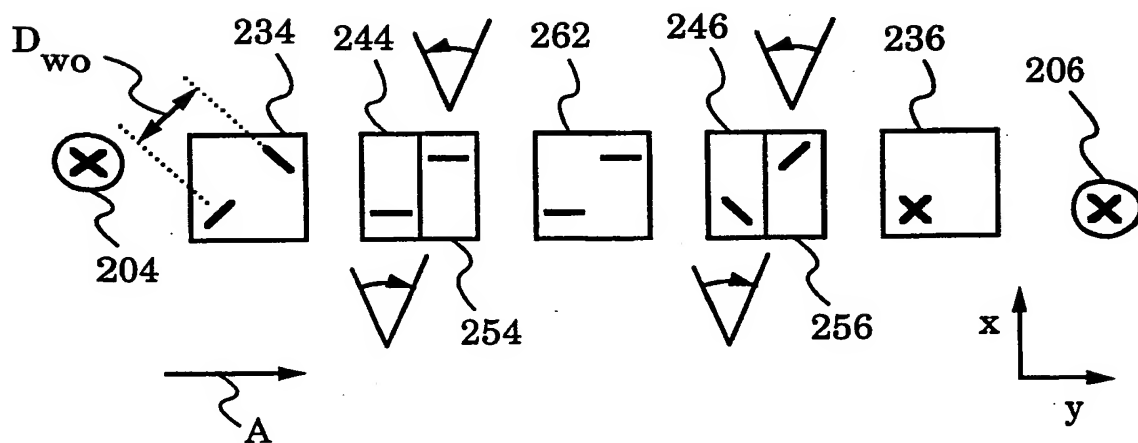
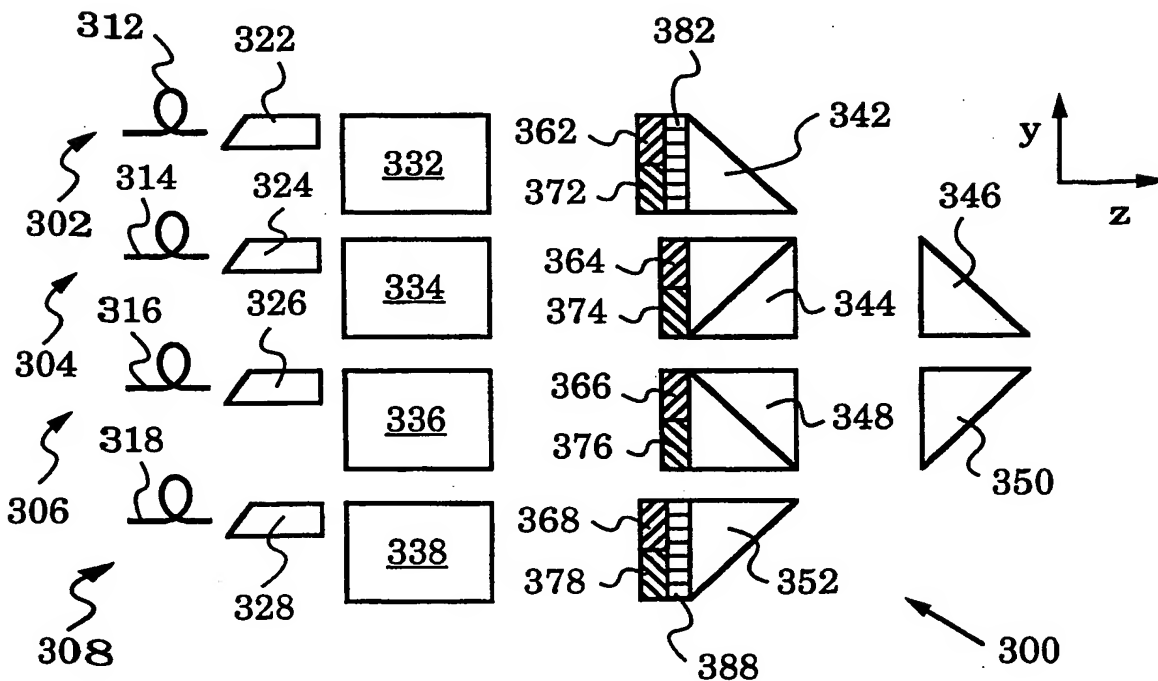
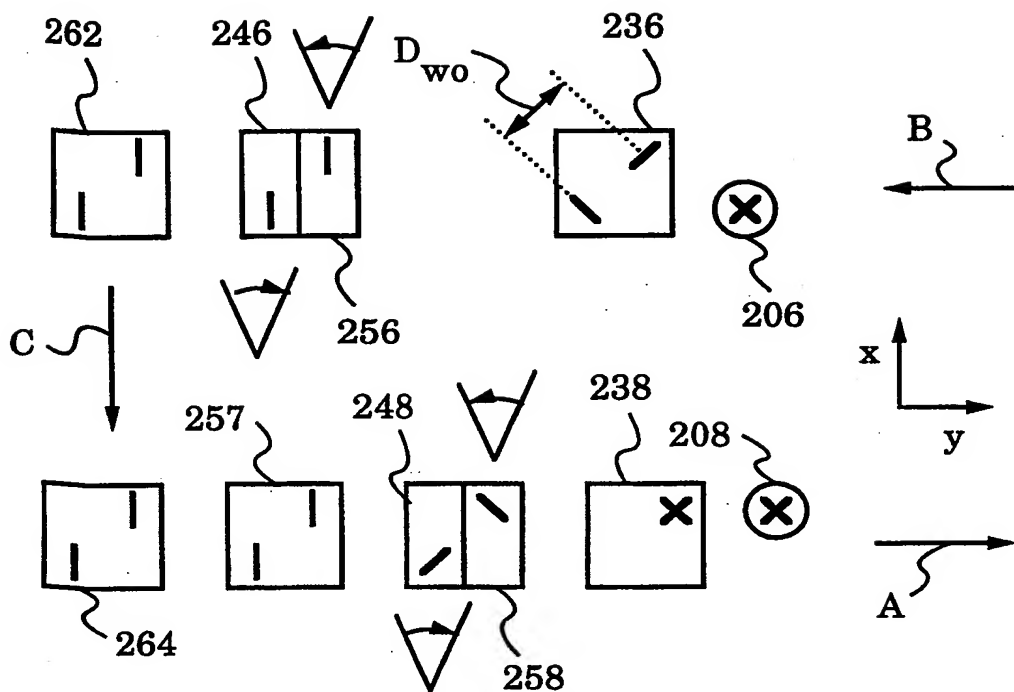


FIG. 7B

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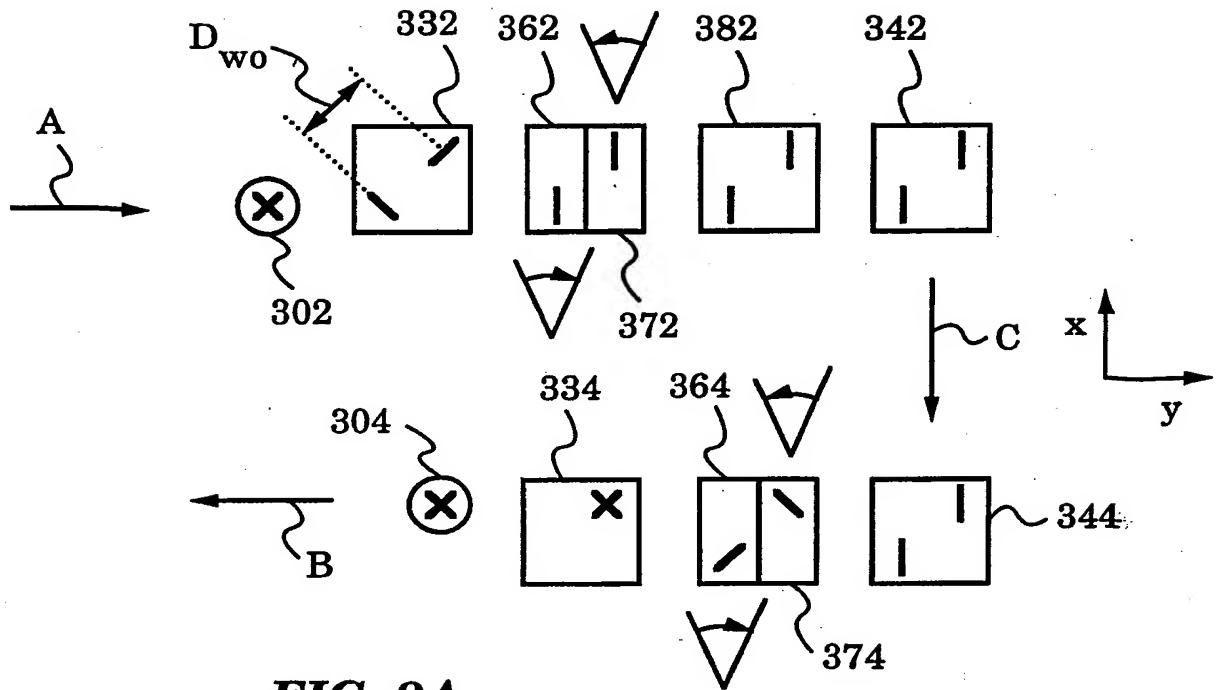


FIG. 9A

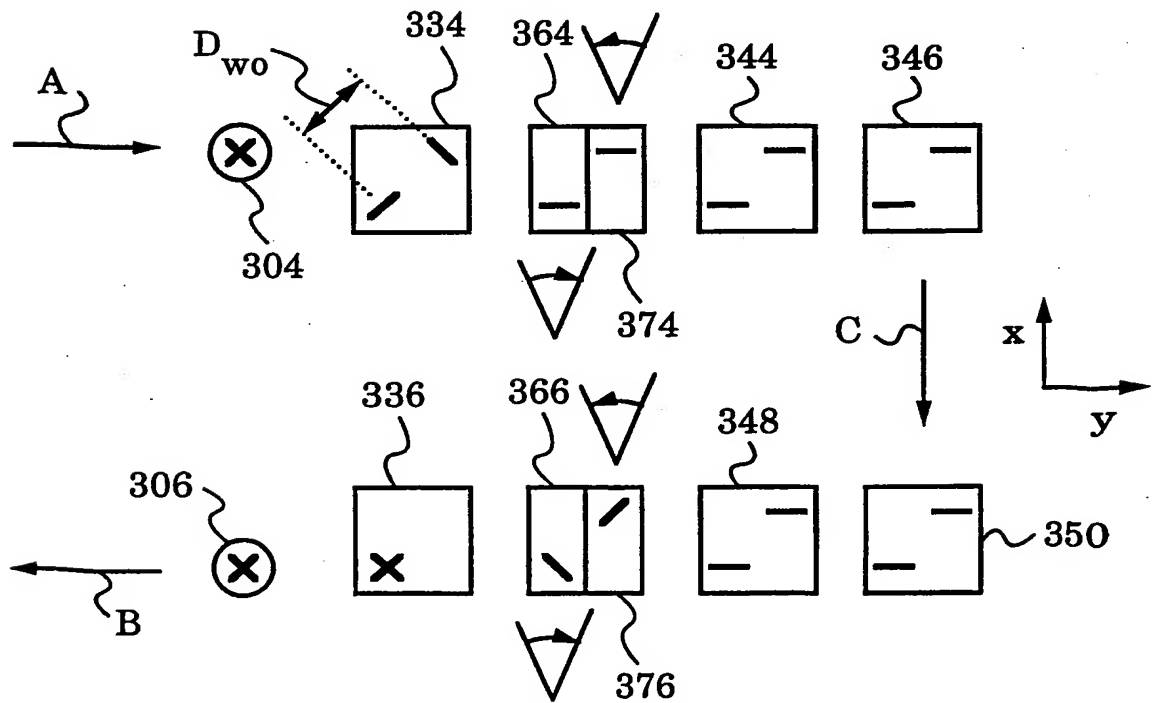


FIG. 9B

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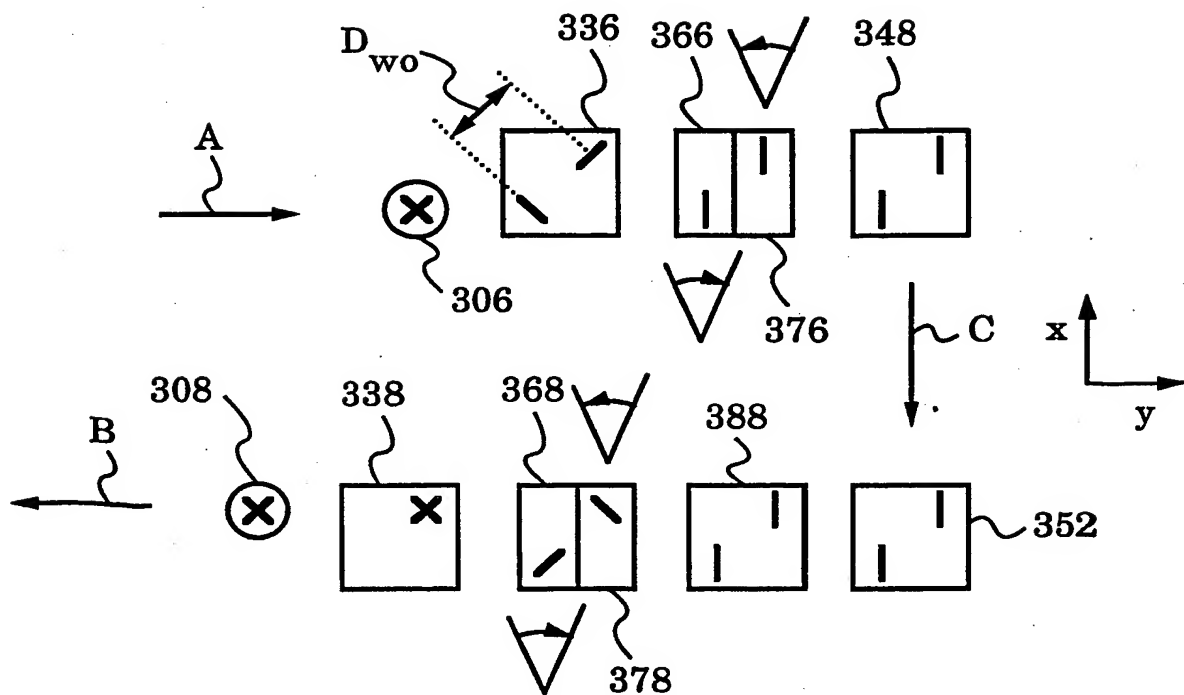


FIG. 9C

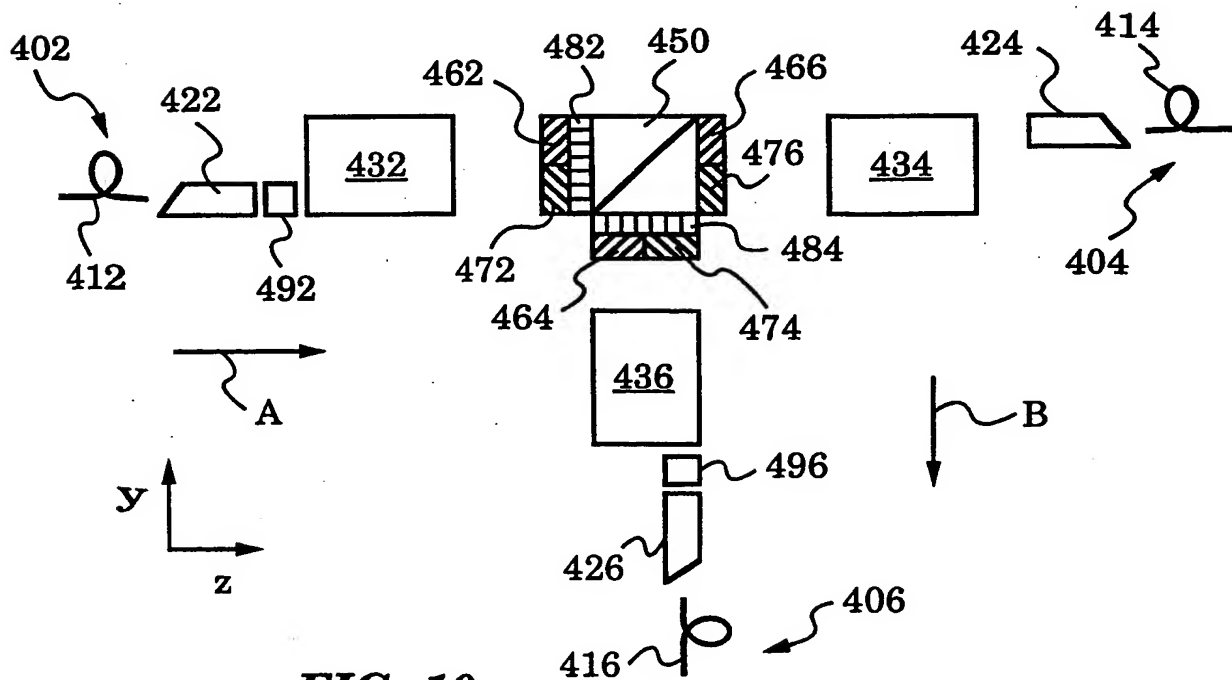


FIG. 10